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A METHOD FOR CORRELATING THE COOLING DATA OF LIQUID-COOLED ENGINES AND ITS APPLICATION TO THE ALLISON V-3420-11 ENGINE

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MEMORANDUM REPORT

for the

Army Air Forces, Air Technical Service Command

A METHOD FOR CORRELATING THE COOLING DATA OF LIQUID-COOLED ENGINES AND ITS APPLICATION TO THE ALLISON V-3420-11 ENGINE

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SUMMARY

A study has been made of the heat-transfer processes in liquid-cooled engines and an equation has been developed that relates the heat rejection to the coolant and the engine operating conditions. Tests of an Allison V-3420-11 engine have been made to check the accuracy of the equation and to establish the cooling characteristics of the engine. By determining the few constants of the equation, the heat rejection to the coolant may be predicted with good accuracy for any particular engine operating condition. The tests showed that the rate of heat dissipation to the coolant was only slightly affected by either the rate of coolant flow or the relative proportions of ethylene glycol and water composing the coolant mixture.

INTRODUCTION

An analysis has been made of the heat-transfer processes in liquid-cooled engines to determine the effects of the various engine and cooling parameters upon the heat rejection to the coolant. This analysis parallels the analysis of heat-transfer processes in air-cooled engines presented in reference 1.

In the analysis of reference 1, equations were developed that relate the cylinder temperatures and the engine operating conditions. These equations have proved very useful in providing a means of completely determining the cooling characteristics of air-cooled engines with a minimum of testing. In the present report somewhat similar equations are developed that give the heat rejection of liquid-cooled engines as a function of the engine operating conditions.

Tests of an Allison V-3420-11 24-cylinder, liquid-cooled engine installed in an XB-39 nacelle were made to check the analysis and to determine the heat-rejection characteristics of this engine. The tests were made over a wide range of engine operating conditions. The coolants used were ethylene glycol, water, and two mixtures of ethylene glycol and water.

SYMBOLS

A, A', B, a, b, d, f, m, n	constants
c_p	specific heat of fluid at constant pressure, Btu per pound per $^{\circ}F$
c_{p_a}	specific heat of air at constant pressure, Btu per pound per $^{\circ}F$
c_{p_c}	specific heat of coolant at constant pressure, Btu per pound per $^{\circ}F$
c_{p_g}	specific heat of combustion gases at constant pressure, Btu per pound per $^{\circ}F$
g	acceleration due to gravity, feet per second per second
H	rate of heat transfer, Btu per second
H_c	rate of heat transfer from cylinder walls to coolant, Btu per second
H_g	rate of heat transfer from combustion gases to cylinder walls, Btu per second
h	surface heat-transfer coefficient, Btu per second per square foot per $^{\circ}F$
J	mechanical equivalent of heat, foot-pounds per Btu
k	thermal conductivity of fluid, Btu per second per square foot per $^{\circ}F$ through 1 foot

k_c	thermal conductivity of coolant, Btu per second per square foot per $^{\circ}F$ through 1 foot
k_g	thermal conductivity of combustion gases, Btu per second per square foot per $^{\circ}F$ through 1 foot
l	linear dimension of fluid passageway, feet
S	surface area in contact with fluid, square feet
t_c	average coolant temperature through engine, $^{\circ}F$
t_{carb}	carburetor-air temperature, $^{\circ}F$
t_f	average temperature of fluid, $^{\circ}F$
t_g	effective gas temperature, $^{\circ}F$
t_{g_o}	effective gas temperature for 0° F intake-air temperature, $^{\circ}F$
t_w	average cylinder-wall temperature, $^{\circ}F$
t_w'	temperature of cylinder wall measured with embedded thermocouples at locations shown in figure 3, $^{\circ}F$
V	average velocity of fluid, feet per second
V_t	impeller tip speed, feet per second
W_c	coolant flow rate, pounds per second
W_e	engine-air flow rate, pounds per hour
Δt_b	blower temperature rise, $^{\circ}F$
ΔT_c	coolant temperature rise through engine, $^{\circ}F$
μ	absolute viscosity of fluid, slugs per second per foot
μ_c	absolute viscosity of coolant, slugs per second per foot
μ_g	absolute viscosity of combustion gases, slugs per second per foot
ρ	density of fluid, slugs per cubic foot

N engine speed, rpm

p_m manifold pressure, inches of mercury absolute

$$Z = \frac{1}{A\frac{k_c}{\mu_c d}\left(\frac{c_{p_c}\mu_c g}{k_c}\right)^{0.4} W_c^{d}}$$

F correction factor applied to obtain Z (fig. 9(b))

K_F correction factor for fuel-air ratio (fig. 13)

K_N correction factor for engine speed (fig. 13)

ANALYSIS

An understanding of the factors determining the amount of heat rejected to the coolant in a liquid-cooled engine can be obtained from a study of the processes by which heat is transferred from the combustion gases to the cylinder walls and from the cylinder walls to the coolant. It has been shown that nearly all the heat transferred from the combustion gases to the cylinder walls is transferred by forced convection. Heat may be transferred from the cylinder walls to the coolant either by forced convection or, if the temperature of the coolant is sufficiently high, by a combination of forced convection and boiling.

Tests have shown that, in general, moderate boiling or vaporization of the coolant in a liquid-cooled engine has little effect upon the over-all rate of heat transfer. Results of tests of an Allison V-1710-81 engine at the NACA Aircraft Engine Research Laboratory, Cleveland, Ohio, indicated that reducing the coolant pressure from 30 to 15 pounds per square inch absolute increased the heat transfer not more than about 3 percent, even though in some cases violent boiling occurred. During the present investigation of the Allison V-3420-11 engine, preliminary tests showed that varying the coolant temperature as much as 80° F resulted in a variation in heat transfer approximately equal to that which would be expected for a forced-convection process. Some evidence indicates that with very violent boiling, particularly at low coolant flows, the heat transfer is affected to a fairly large degree. For normal engine operation, however, the effect of moderate boiling may be neglected and in the present report the heat to the coolant will be considered to be transferred entirely by forced convection.

Dimensional analysis has shown and experiment has verified that for heat transfer by forced convection the Nusselt number $\frac{hl}{k}$ is a function of the Reynolds number $\frac{\rho V l}{\mu}$ and the Prandtl number $\frac{c_p \mu g}{k}$. Test data have indicated that these functions are simple exponential functions for either laminar flow or fully developed turbulent flow; that is,

$$\frac{hl}{k} \propto \left(\frac{\rho V l}{\mu}\right)^m \left(\frac{c_p \mu g}{k}\right)^n \tag{1}$$

where m and n are constant over fairly wide ranges of Reynolds and Prandtl numbers, except in the transition region between laminar and turbulent flow. The rate of heat transfer is given by the relationship

$$H = hS(t_f - t_w) \tag{2}$$

where S is the surface area over which the fluid flows and t_f and t_w are the average temperatures of the fluid and wall, respectively. Equations (1) and (2) may be combined to give

$$H \propto S\frac{k}{l} \left(\frac{\rho V l}{\mu}\right)^m \left(\frac{c_p \mu g}{k}\right)^n (t_f - t_w) \tag{3}$$

For the heat-transfer process from the combustion gases to the cylinder walls, l in equation (3) is some representative internal dimension of the cylinder. Since l and S are constant for a particular engine and since the engine-air flow W_e is proportional to ρV, the heat transferred from the combustion gases is

$$H_g \propto W_e^{\,a}\,\frac{k_g}{\mu_g^{\,a}}\left(\frac{c_{p_g}\mu_g g}{k_g}\right)^b (t_g - t_w) \qquad (4)$$

where t_g is the effective temperature of the gases within the cylinder over the entire cycle and the values of k_g, μ_g, and c_{p_g} are also effective values over the entire cycle. It is indicated in reference 1 that the value of the term $\frac{k_g}{\mu_g^{\,a}}\left(\frac{c_{p_g}\mu_g g}{k_g}\right)^b$ does not vary appreciably with changes in engine operating conditions. More recent data on the effect of temperature and fuel-air ratio upon the physical properties of mixtures of fuel and air after combustion (references 2 and 3) indicate that $\frac{k_g}{\mu_g^{\,a}}\left(\frac{c_{p_g}\mu_g g}{k_g}\right)^b$ may vary appreciably with changes in engine fuel-air ratio. Since t_g is also a function of fuel-air ratio, however, the variations of $\frac{k_g}{\mu_g^{\,a}}\left(\frac{c_{p_g}\mu_g g}{k_g}\right)^b$ may, to a first approximation, be included in the effective gas temperature. Equation (4) may therefore be written

$$H_g \propto W_e^{\,a}\,(t_g - t_w) \qquad (5)$$

where t_g may be defined as the temperature that most nearly satisfies equation (5) and is a function of only fuel-air ratio, intake-air temperature, spark timing, and exhaust back pressure. A large number of tests have shown that equation (5) is very accurate for air-cooled engines; this equation may be expected to be equally accurate for liquid-cooled engines.

The rate of heat transfer from the cylinder walls to the coolant is, by a similar analysis,

$$H_c \propto W_c{}^d \frac{k_c}{\mu_c{}^d}\left(\frac{c_{p_c}\mu_c g}{k_c}\right)^f (t_w - t_c)$$

or

$$H_c = AW_c{}^d \frac{k_c}{\mu_c{}^d}\left(\frac{c_{p_c}\mu_c g}{k_c}\right)^f (t_w - t_c) \qquad (6)$$

The value of the term $\frac{k_c}{\mu_c{}^d}\left(\frac{c_{p_c}\mu_c g}{k_c}\right)^f$ in this case depends upon the proportions of ethylene glycol and water used as the coolant and upon the coolant temperature.

Because of the heat generated by friction between the piston rings and the cylinder barrels, the cooling of the pistons and barrels by the oil, and the cooling of the exposed surfaces of the cylinder block, the heat transferred from the combustion gases to the cylinder walls H_g is not equal to the heat transferred to the coolant H_c. It is assumed, however, that

$$H_c \propto H_g$$

Therefore, from equation (5),

$$H_c = BW_e{}^a (t_g - t_w) \qquad (7)$$

or

$$t_w = t_g - \frac{H_c}{BW_e{}^a}$$

Substituting $t_g - \frac{H_c}{BW_e{}^a}$ for t_w in equation (6) yields

$$H_c = AW_c^{\,d} \frac{k_c}{\mu_c^{\,d}} \left(\frac{c_{p_c}\mu_c g}{k_c}\right)^f \left(t_g - t_c - \frac{H_c}{BW_e^{\,a}}\right)$$

and

$$\frac{t_g - t_c}{H_c} = \frac{1}{BW_e^{\,a}} + \frac{1}{A \dfrac{k_c}{\mu_c^{\,d}} \left(\dfrac{c_{p_c}\mu_c g}{k_c}\right)^f W_c^{\,d}} \qquad (8)$$

Equation (8) is used in the present report to correlate the data obtained on the V-3420-11 engine.

For a single coolant mixture and coolant temperature, the physical properties of the coolant are constant and equation (8) may be rewritten as

$$\frac{t_g - t_c}{H_c} = \frac{1}{BW_e^{\,a}} + \frac{1}{A'W_c^{\,d}} \qquad (9)$$

ENGINE AND INSTRUMENTATION

The Allison V-3420-11 engine tested is a 24-cylinder, double-vee, liquid-cooled engine, having a normal-power rating of 2100 horsepower at 2600 rpm and a military-power rating of 2600 horsepower at 3000 rpm. The engine has a compression ratio of 6.65:1, a propeller-gear ratio of 3.13:1, and a blower-gear ratio of 6.9:1. The impeller diameter is 10 inches. The engine is equipped with a Bendix-Stromberg PR58B3 carburetor. A view of the engine nacelle as set up for the tests is shown in figure 1.

The coolant system for this engine installation had two radiators, one for each half of the engine. The coolant flow from each half of the engine was measured by an annular-orifice flowmeter. A close agreement with these flow measurements was obtained from pitot-static flowmeters that measured the flow into the individual cylinder blocks.

The coolant temperature rise was measured by three thermocouples across each half of the engine. The hot and cold junctions of these thermocouples were located in the coolant piping near the engine outlet and inlet, respectively. A hand-balanced potentiometer was used to indicate the coolant temperature difference existing between the hot and cold junctions. In general, the coolant temperature rise through the engine is difficult to measure accurately. Some of the difficulty is due to the fact that the over-all temperature difference is small throughout the engine operating range. Limitations in space available for the installation of thermocouples present an additional practical problem. The accuracy of the method used in these tests is estimated to be ±4 percent. The temperature of the coolant entering the engine was measured by a resistance thermometer in conjunction with a special microammeter.

A sketch of part of the coolant system, which shows the points of flow and temperature measurement for the left half of the engine, is given as figure 2. The instrumentation for the coolant system on the right half of the engine was similar to that shown for the left half.

Cylinder temperatures were measured by embedded thermocouples and spark-plug-gasket thermocouples. Embedded thermocouples were located between the intake valves, between the exhaust valves, and in the exhaust spark-plug bosses (as shown in fig. 3) of cylinders 1, 2, 3, 4, 5, and 6 of the left bank and 1, 3, and 6 of each of the other three banks. Cylinder-barrel temperatures were not measured because of the difficulty of installing thermocouples. The carburetor-air temperature was measured by two thermocouples soldered to the carburetor screen.

The engine-air flow was measured by a calibrated venturi (fig. 1). Fuel flow was measured by rotameters and a weigh tank. Standard aircraft instruments were used to measure manifold pressure and engine speed. A special mercury U-tube manometer was also used to measure manifold pressure for some of the tests.

METHODS AND TESTS

Tests were made with the following four coolant mixtures: (a) 100 percent ethylene glycol (AN-E-2), (b) 80 percent by volume ethylene glycol (AN-E-2) and 20 percent water, (c) 30 percent by volume ethylene glycol (AN-E-2) and 70 percent water, and (d) water.

In order to reduce coolant boiling during the tests with the 30-70 mixture and with water, the coolant system was pressurized by applying compressed air to the expansion tank. A sight glass was installed to indicate the coolant level. No appreciable increase in the coolant level was observed during any of the tests - an indication that large vapor pockets did not form.

The properties of the coolants were obtained from reference 4. Curves showing these properties for mixtures of pure ethylene glycol and water have been plotted from the data of reference 4 and are presented in figure 4. Ethylene glycol (AN-E-2) was considered to be 97 percent by volume pure ethylene glycol and 3 percent water, with the effect of the inhibitor neglected.

The heat rejection to the coolant was determined by use of the following equation:

$$H_c = W_c c_{p_c} \Delta T_c \tag{10}$$

where ΔT_c is the temperature rise of the coolant measured across the engine.

The constant f in equation (6) was assumed to equal 0.4 as found by Sherwood and Petrie (reference 5). The constants A and d were determined from a plot of

$$\frac{H_c}{k_c \left(\frac{c_{p_c} \mu_c g}{k_c}\right)^{0.4} (t_w - t_c)}$$

against W_c/μ_c on logarithmic paper. The term $t_w - t_c$ was found from the equation

$$t_w - t_c = 0.64(t_w' - t_c) \tag{11}$$

where t_w' is the average temperature measured by the thermocouples embedded in the cylinder block between the intake valves, between the exhaust valves, and in the exhaust spark-plug bosses. The factor 0.64 was obtained from unpublished data from tests at the Cleveland Laboratory of an Allison V-1710 engine in which temperatures were measured at various other points on the cylinder in addition to those between the valves and in the exhaust spark-plug boss. It was found that equation (11) holds closely for all operating conditions. Inasmuch as the cylinders of the V-3420-11 and V-1710 engines are nearly identical, it may be expected that this relationship is also valid for the V-3420-11 engine.

No tests were made to determine the effects of spark timing, exhaust back pressure, or intake-air temperature upon t_g. There is no provision on the V-3420-11 engine for varying the spark timing and all the tests were made with normal spark timing. The exhaust back pressure was approximately 30 inches of mercury absolute throughout the tests. The results are not applicable, therefore, at high altitude except for a turbosupercharger installation with the engine operating at high powers.

It has been assumed that, as was found for the cylinder head of an air-cooled engine (reference 6), t_g increases approximately 0.8° per degree rise in intake-air temperature; that is,

$$t_g = t_{g_o} + 0.8\left(t_{carb} + \Delta t_b\right)$$

where t_{carb} is the carburetor-air temperature and Δt_b is the blower temperature rise. The blower rise was calculated from the following equation:

$$\Delta t_b = \frac{V_t^2}{c_{p_a} Jg}$$

where c_{p_a} is the specific heat of air at constant pressure and V_t is the impeller tip speed. For the V-3420-11 engine, this equation may be written

$$\Delta t_b = 0.0000151N^2$$

where N is engine speed in revolutions per minute.

In order to determine the actual value of t_{g_o} at a fuel-air ratio of 0.08, tests were made at constant engine operating conditions and varying coolant temperatures. Since, with constant W_e,

$$H_c \propto t_g - t_w$$

$$\propto t_{g_o} + 0.8(t_{carb} + \Delta t_b) - t_w$$

t_{g_o} was found by plotting $t_w - 0.8(t_{carb} + \Delta t_b)$ against H_c and extrapolating the resulting curves to $H_c = 0$ for which

$$t_{g_o} = t_w - 0.8(t_{carb} + \Delta t_b)$$

The values of t_w used were obtained from the equation

$$t_w = \frac{H_c}{A \dfrac{k_c}{\mu_c{}^d} \left(\dfrac{c_{p_c}\mu_c g}{k_c}\right)^{0.4} W_c{}^d} + t_c$$

The coolant mixture used for these tests was 100 percent ethylene glycol (AN-E-2).

Tests were made at various fuel-air ratios with engine speed and engine-air flow held constant to determine the value of t_{g_o} at fuel-air ratios other than 0.08. With t_c, W_c, and W_e held constant, the value of t_{g_o} could be found for the different fuel-air ratios from the equation

$$\frac{t_g - t_c}{H_c} \doteq \text{Constant}$$

The value of the constant was determined from the measured values of t_c and H_c at a fuel-air ratio of 0.08 and the value of $t_{g_o} + 0.8(t_{carb} + \Delta t_b)$ previously determined for a fuel-air ratio of 0.08.

Tests were made at various engine speeds, engine powers, and fuel-air ratios with each of the four coolants. The value of

$$\frac{t_g - t_c}{H_c} - \frac{1}{A \dfrac{k_c}{{\mu_c}^d} \left(\dfrac{c_{p_c} \mu_c g}{k_c}\right)^f {W_c}^d}$$

was determined for each test and plotted against W_e on logarithmic coordinates.

RESULTS AND DISCUSSION

The plot of

$$\frac{H_c}{k_c \left(\dfrac{c_{p_c} \mu_c g}{k_c}\right)^{0.4} (t_w - t_c)}$$

against W_c/μ_c from which the values of d and A of equations (6) and (8) were determined is shown in figure 5. It may be seen that the slope d of the curve of figure 5 is not constant but decreases with increasing W_c/μ_c, as is usually observed for the transition region between laminar and fully developed turbulent flow.

Separate values of d and A were selected from figure 5 for each of the coolants tested. These values are as follows:

Coolant mixture (percent by volume)		d	A
Ethylene glycol (AN-E-2)	Water		
100	0	0.34	309
80	20	.28	728
30	70	.17	3,750
0	100	.095	11,600

The value of t_{g_o} at a fuel-air ratio of 0.08 was determined from the plot shown in figure 6. On an average the data indicate that t_{g_o} for the entire cylinder is approximately 700° F. Because of the large extrapolation necessary in figure 6, values of 600° F and 800° F for t_{g_o} at a fuel-air ratio of 0.08 were also used in calculating the test data. Closer correlation between the heat rejection to the coolant and the engine operating conditions was obtained by using 700° F than by using either 600° F or 800° F. The data obtained by using 600° F and 800° F are not given in the present report.

A value of approximately 900° F for t_{g_o} for the entire cylinder of an air-cooled engine was calculated from data given in reference 1 for a Pratt & Whitney R-1340-H cylinder and in reference 6 for a Wright R-1820-G cylinder. The reason for the lower value of 700° F obtained for t_{g_o} for the V-3420-11 cylinder is not entirely understood but this lower value may in part be due to better scavenging of the V-3420-11 cylinder, which has two intake and exhaust valves with a comparatively large valve overlap of 65°. Differences in cylinder construction, compression ratio, or spark timing may also have contributed to the differences in t_{g_o} between these engines.

The effect of fuel-air ratio upon t_{g_o} is shown in figure 7. Figure 8 shows

$$\frac{t_g - t_c}{H_c} = \frac{1}{A \dfrac{k_c}{\mu_c^{\,d}} \left(\dfrac{c_{p_c}\mu_c g}{k_c}\right)^{0.4} W_c^{\,d}}$$

plotted against W_e. Some of the scatter in figure 8 can be attributed to the limited accuracy of the method used to measure the coolant temperature rise.

The heat-transfer equations obtained from equation (8) and figures 8 and 5 are as follows:

Coolant mixture (percent by volume)		Heat-transfer equation
Ethylene glycol (AN-E-2)	Water	
100	0	$\frac{t_g - t_c}{H_c} = \frac{1}{309 \dfrac{k_c}{\mu_c^{0.34}} \left(\dfrac{c_{p_c}\mu_c g}{k_c}\right)^{0.4} W_c^{0.34}} = 135 W_e^{-0.52}$
80	20	$\frac{t_g - t_c}{H_c} = \frac{1}{728 \dfrac{k_c}{\mu_c^{0.28}} \left(\dfrac{c_{p_c}\mu_c g}{k_c}\right)^{0.4} W_c^{0.28}} = 135 W_e^{-0.52}$
30	70	$\frac{t_g - t_c}{H_c} = \frac{1}{3{,}750 \dfrac{k_c}{\mu_c^{0.17}} \left(\dfrac{c_{p_c}\mu_c g}{k_c}\right)^{0.4} W_c^{0.17}} = 135 W_e^{-0.52}$
0	100	$\frac{t_g - t_c}{H_c} = \frac{1}{11{,}600 \dfrac{k_c}{\mu_c^{0.095}} \left(\dfrac{c_{p_c}\mu_c g}{k_c}\right)^{0.4} W_c^{0.095}} = 135 W_e^{-0.52}$

The values of the second term of these equations

$$\frac{1}{A\,\frac{k_c}{\mu_c{}^d}\left(\frac{c_{p_c}\mu_c g}{k_c}\right)^{0.4} W_c{}^d}$$

for various coolant mixtures, coolant temperatures, and coolant flow rates are presented in figure 9. For convenience in the use of these curves,

$$\frac{1}{A\,\frac{k_c}{\mu_c{}^d}\left(\frac{c_{p_c}\mu_c g}{k_c}\right)^{0.4} W_c{}^d}$$

is denoted by Z in figure 9.

The small effect of changes in coolant flow rate and coolant properties upon the engine heat rejection may be seen from the foregoing heat-transfer equations. The value of the term

$$\frac{1}{309\,\frac{k_c}{\mu_c{}^{0.34}}\left(\frac{c_{p_c}\mu_c g}{k_c}\right)^{0.4} W_c{}^{0.34}}$$

for 100 percent ethylene glycol (AN-E-2) at normal power is approximately 0.20, whereas $\frac{t_g - t_c}{H_c}$ is approximately 1.15. An increase in coolant flow W_c of 50 percent results in an increase in heat transfer of only 2.5 percent if other conditions remain constant. A change in coolant to a mixture of 30 percent ethylene glycol (AN-E-2) and 70 percent water results in a value of

$$\frac{1}{3750\ \frac{k_c}{\mu_c^{0.17}}\left(\frac{c_{p_c}\mu_c g}{k_c}\right)^{0.4} W_c^{0.17}}$$

of approximately 0.145, which would cause an increase in heat transfer of about 5 percent.

The variation in average cylinder-wall temperature t_w with changes in coolant flow rate or coolant properties may be found from the resulting change in H_c and from the equation

$$H_c = BW_e^{a}(t_g - t_w)$$

If W_e is constant,

$$H_c \propto t_g - t_w$$

Because of the small effect upon the heat rejection of variations in

$$\frac{1}{A\ \frac{k_c}{\mu_c^{d}}\left(\frac{c_{p_c}\mu_c g}{k_c}\right)^{0.4} W_c^{d}}$$

with changes in coolant flow rate W_c and average engine coolant temperature t_c, the test data for individual coolant mixtures may be plotted as shown in figure 10. By plotting $\frac{H_c}{t_g - t_c}$ against W_e, curves are obtained from which the heat rejection H_c may be determined with only a small sacrifice in accuracy much more easily than from figure 8.

It was assumed in the analysis that the heat generated by friction between the piston rings and the cylinder barrels has little effect upon the heat rejection to the coolant. Tests were made with constant engine-air consumption at various engine speeds to determine the error involved in the use of this assumption. The data indicated that

$$\frac{t_g - t_c}{H_c} = \frac{1}{A \dfrac{k_c}{\mu_c{}^d} \left(\dfrac{c_{p_c} \mu_c g}{k_c}\right)^{0.4} W_c{}^d}$$

decreases slightly with increasing engine speed, but an accurate evaluation of this effect was not possible primarily because of the limited accuracy of the method used to measure the coolant temperature rise.

In order to relate the cooling characteristics of the engine to variables measured by the usual engine instruments, calibration curves of W_c and W_e are presented in figures 11 and 12, respectively. Figure 11 shows that the proportions of water and ethylene glycol used for the coolant have little effect upon the rate of coolant flow. If cavitation occurs at the coolant pump inlet, however, the flow may be considerably less than that shown in figure 11. In preparing figure 12, the engine-air flow W_e was assumed to be a function of only the engine speed, manifold pressure, exhaust back pressure, and the sum of the absolute carburetor-air temperature and the blower temperature rise $t_{carb} + 460 + \Delta t_b$. Data from the Allison Division of General Motors Corp. indicate that the engine-air flow varies inversely as $\sqrt{t_{carb} + 460 + \Delta t_b}$. Curves of

$\dfrac{W_e}{\sqrt{t_{carb} + 460 + \Delta t_b}}$ against engine speed are plotted in figure 12 for various manifold pressures. Throughout the tests, the maximum difference between the measured engine-air flow and the corresponding values given by figure 12 was less than 4 percent. No data were available concerning the effect of exhaust back pressure upon engine-air flow.

The variation of brake horsepower with engine operating conditions may be determined from the following empirical relation obtained from the Allison Division:

$$\text{Brake horsepower} = \left[\frac{p_m}{1 + \frac{t_{carb} - 80}{10}(0.01)}\right]\frac{K_N}{K_F} - 700$$

where

p_m manifold pressure, inches of mercury absolute

t_{carb} carburetor-air temperature, $^{\circ}F$

K_N correction factor for engine speed (fig. 13)

K_F correction factor for fuel-air ratio (fig. 13)

The data obtained during the tests are presented in table I.

APPLICATION

Through the use of the curves presented in the present report, the heat rejection to the coolant for the Allison V-3420-11 engine may be determined for any particular engine operating condition. The following example, based on engine operation at military power (2600 bhp at 3000 rpm and a manifold pressure of 44.5 in. of mercury absolute), illustrates the procedure: Typical operating conditions assumed are

Carburetor-air temperature, t_{carb}, $^{\circ}F$ 80
Fuel-air ratio 0.095
Coolant temperature out of engine, $^{\circ}F$ 250
Coolant mixture . . . . . 70 percent by volume ethylene glycol (AN-E-2)

For engine operation at 3000 rpm and 44.5 inches of mercury absolute, figure 12 indicates that

$$\frac{W_e}{\sqrt{t_{carb} + 460 + \Delta t_b}} = 697$$

The blower temperature rise is

$$\Delta t_b = \frac{V_t^2}{c_{p_a} Jg}$$

$$= 0.0000151N^2$$

$$= 0.0000151(3000)^2$$

$$= 135.9^\circ \text{ F}$$

Solving for the engine-air flow yields

$$W_e = 697\sqrt{t_{carb} + 460 + \Delta t_b}$$

$$= 697\sqrt{80 + 460 + 136}$$

$$= 18{,}100 \text{ pounds per hour}$$

For an engine-air flow of 18,100 pounds per hour (fig. 8),

$$\frac{t_g - t_c}{H_c} = \frac{1}{A \dfrac{k_c}{\mu_c{}^d}\left(\dfrac{c_{p_c}\mu_c g}{k_c}\right)^{0.4} W_c{}^d} = 0.820$$

In order to determine the value of

$$\frac{1}{A \dfrac{k_c}{\mu_c{}^d}\left(\dfrac{c_{p_c}\mu_c g}{k_c}\right)^{0.4} W_c{}^d}$$

it is necessary to know the coolant flow rate W_c and the average engine coolant temperature t_c. From figure 11, W_c = 78 pounds per second at 3000 rpm. It was found during the tests that the average engine coolant temperature was approximately 5° F lower than the coolant temperature out of the engine over a wide range of operating conditions; therefore, let t_c = 245° F. Then, from figure 9(a), for a coolant mixture of 70 percent by volume ethylene glycol (AN-E-2), a coolant flow rate of 78 pounds per second, and an average engine coolant temperature of 250° F, the term

$$\frac{1}{A \dfrac{k_c}{\mu_c{}^d}\left(\dfrac{c_{p_c}\mu_c g}{k_c}\right)^{0.4} W_c{}^d}$$

denoted by $Z_{(t_c=250)}$ is equal to 0.160. In order to correct this term to the desired value of t_c, 245° F, for the same W_c and coolant mixture, the correction factor F in figure 9(b) is found to be 0.993. Therefore,

$$Z = FZ_{(t_c=250)}$$

$$= 0.993 \times 0.160$$

$$= 0.159$$

Then

$$\frac{t_g - t_c}{H_c} - 0.159 = 0.820$$

or

$$H_c = \frac{t_g - t_c}{0.979}$$

For a fuel-air ratio of 0.095, $t_{g_o} = 649^\circ$ F from figure 7.

Then

$$t_g = t_{g_o} + 0.8(t_{carb} + \Delta t_b)$$

$$= 649 + 0.8(80 + 136)$$

$$= 822^\circ \text{ F}$$

Since $t_c = 245^\circ$ F,

$$H_c = \frac{t_g - t_c}{0.979}$$

$$= \frac{822 - 245}{0.979}$$

$$= 589 \text{ Btu per second}$$

The Allison Division guarantees that the heat rejection to the coolant at military power shall not exceed 608 Btu per second, which is approximately 3 percent above the heat rejection calculated in the preceding example.

CONCLUSIONS

As a result of an analysis made of the heat-transfer processes in liquid-cooled engines, an equation has been developed that relates the heat rejection to the coolant and the engine operating conditions. Tests of an Allison

V-3420-11 engine over a wide range of operating conditions and for several coolant mixtures showed that:

1. By determining the constants of the equation, the heat rejection to the coolant may be predicted with good accuracy for any particular operating condition.

2. The rate of coolant flow had only a slight effect upon the rate of heat dissipation to the coolant; also, the effect of the relative proportions of ethylene glycol and water composing the coolant mixture upon the heat-dissipation rate was small.

3. Changes in engine friction with engine speed had a small effect upon the heat rejection to the coolant; an accurate evaluation of this effect was not made.

4. The effective gas temperature for an entire cylinder of the V-3420-11 engine was approximately 700° F for a fuel-air ratio of 0.08 and an intake-air temperature of 0° F.

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National Advisory Committee for Aeronautics
Langley Field, Va.

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TABLE I.- RESULTS OF TESTS OF ALLISON V-3420-11 ENGINE

[Engine serial no. 42-271081; compression ratio, 6.65 to 1; spark timing, intake 28° B.T.C., exhaust 34° B.T.C.; carburetor, Bendix-Stromberg PR58B3; fuel, AN-F-28; oil, AN-VV-O-446, grade 1120]

Test	Manifold pressure (in. Hg abs.)	Engine speed (rpm)	Carburetor-air temperature (°F)	Barometric pressure (in. Hg abs.)	Fuel flow (lb/hr)	Engine-air flow (lb/hr)	Fuel-air ratio	Coolant-system pressure (lb/sq in. gage)	Coolant temperature into engine (°F)	Engine coolant temperature rise (°F)			Average engine coolant temperature (°F)	Engine coolant flow (lb/sec)			Cylinder-wall temperature (°F)				Engine heat rejection (Btu/sec)	Oil temperature into engine (°F)
																	Embedded thermocouple		Spark-plug-gasket thermocouple			
										Left half	Right half	Av.		Left half	Right half	Total	Av.	Max.	Av.	Max.		
Coolant mixture, 80 percent by volume ethylene glycol (AN-E-2)																						
1	30.0	1900	90	30.16	613	7050	0.0870	---------	207	10.3	9.9	10.1	212	24.4	22.1	46.5	327	415	272	297	353	166
2	30.0	1900	90	30.14	569	7100	.0802	---------	215	10.5	10.3	10.4	220	24.4	22.2	46.6	344	429	281	302	367	167
3	30.0	1900	69	30.32	574	7180	.0799	---------	224	10.0	10.6	10.3	229	24.2	22.4	46.6	337	438	279	303	366	167
4	30.0	1900	70	30.32	551	7180	.0768	---------	226	10.5	10.4	10.5	231	24.3	22.3	46.6	332	432	278	302	373	167
5	30.0	1895	72	30.33	537	7160	.0750	---------	223	10.2	11.2	10.7	229	24.2	22.2	46.4	337	433	273	300	378	166
6	30.0	1900	74	30.34	516	7150	.0722	---------	223	10.3	11.6	11.0	228	24.2	22.2	46.4	336	440	273	297	389	161
7	30.0	1900	87	30.05	602	7410	.0812	---------	222	11.3	10.5	10.9	228	24.3	22.4	46.7	---	----	----	----	388	165
8	30.0	1900	87	30.05	632	7410	.0853	---------	220	11.6	10.6	11.1	226	24.3	22.3	46.6	---	----	----	----	393	165
9	25.0	1500	82	30.04	372	4640	.0802	---------	204	11.1	11.2	11.2	210	18.9	17.0	35.9	---	----	----	----	302	165
10	25.0	1500	81	30.03	384	4640	.0828	---------	204	11.0	11.0	11.0	210	19.0	16.9	35.9	---	----	----	----	297	165
11	25.0	1500	81	30.02	358	4640	.0772	---------	202	11.4	11.8	11.6	208	19.0	17.2	36.2	---	----	----	----	315	165
12	25.0	1500	80	30.02	340	4620	.0736	---------	205	11.6	11.9	11.7	211	18.8	16.9	35.7	---	----	----	----	314	165
13	25.2	1500	84	30.00	324	4690	.0691	---------	200	12.0	13.0	12.5	206	19.1	17.0	36.1	---	----	----	----	338	165
14	25.3	1500	86	30.00	315	4680	.0673	---------	202	11.5	12.9	12.2	208	19.1	17.1	36.2	---	----	----	----	331	165
15	25.3	1500	88	30.00	305	4670	.0653	---------	203	11.3	13.2	12.2	209	18.8	16.9	35.7	---	----	----	----	327	165
16	24.1	1705	86	29.95	373	4710	.0792	---------	205	10.5	10.1	10.3	210	21.7	19.7	41.4	308	384	258	281	320	162
17	26.0	1700	85	29.95	428	5360	.0798	---------	204	11.0	10.5	10.7	209	21.7	19.6	41.3	313	391	264	286	332	164
18	22.0	1700	84	29.95	322	4040	.0797	---------	205	9.5	9.2	9.4	210	21.5	19.5	41.0	301	366	251	268	289	158
19	20.0	1700	83	29.95	277	3470	.0798	---------	207	8.7	8.6	8.6	211	21.7	19.5	41.2	293	353	248	264	266	164
20	28.0	1700	68	30.19	490	6190	.0792	---------	206	11.9	11.0	11.5	212	21.6	19.3	40.9	316	398	264	288	354	164
21	30.0	1700	69	30.19	504	6900	.0730	---------	204	12.4	11.0	11.7	209	21.6	19.3	40.9	314	404	261	285	354	162
22	18.0	1700	69	30.20	235	2890	.0814	---------	204	8.3	8.5	8.4	208	21.6	19.4	41.0	287	340	239	255	258	162
23	16.0	1700	69	30.20	210	2440	.0861	---------	212	7.7	6.6	7.2	216	21.5	19.4	40.9	283	334	240	256	222	167
24	30.0	1700	78	30.05	549	6810	.0806	---------	201	13.0	11.0	12.0	207	21.7	19.6	41.3	312	401	266	285	371	163
25	28.2	1850	80	30.05	547	6800	.0804	---------	204	12.3	10.6	11.5	210	23.5	21.5	45.0	322	409	265	292	389	163
26	27.0	2000	84	30.04	547	6780	.0807	---------	206	11.0	10.1	10.6	212	25.7	23.6	49.3	318	403	266	290	393	163
27	25.4	2150	85	30.04	549	6770	.0811	---------	208	10.0	9.7	9.9	212	28.1	25.8	53.9	320	398	266	288	401	165
28	24.9	2300	81	30.03	547	6860	.0797	---------	205	8.9	9.5	9.2	209	30.1	27.6	57.7	315	388	259	281	398	167
29	23.9	2450	80	30.03	548	6830	.0802	---------	205	8.7	8.9	8.8	210	31.3	30.1	61.4	313	384	262	279	406	167
30	23.1	2600	79	30.03	547	6850	.0798	---------	205	8.3	8.7	8.5	209	32.1	30.8	62.9	308	383	256	276	401	171
31	25.6	1505	76	30.08	315	4730	.0666	---------	207	10.5	11.2	10.9	213	19.7	17.5	37.2	309	371	253	279	305	158
32	25.6	1500	75	30.08	304	4730	.0642	---------	204	10.4	11.6	11.0	209	19.7	17.2	36.9	298	364	249	277	305	158
33	25.3	1510	75	30.10	408	4730	.0862	---------	205	10.7	9.7	10.2	210	19.9	17.6	37.5	295	361	246	262	287	158
34	25.5	1505	75	30.11	397	4730	.0839	---------	206	10.9	10.3	10.6	212	19.9	17.5	37.4	299	365	250	264	298	158
35	25.8	1500	77	30.10	322	4750	.0678	---------	205	11.1	11.5	11.3	210	19.5	17.4	36.9	300	372	259	277	313	158
36	25.8	1500	80	30.10	339	4740	.0715	---------	203	11.6	11.6	11.6	209	19.5	17.4	36.9	303	371	250	275	321	160
37	30.0	2000	80	30.13	764	8100	.0943	---------	209	10.3	9.5	9.9	213	26.9	24.1	51.0	324	402	265	297	380	161
38	30.5	2000	83	30.10	649	8060	.0805	---------	207	11.7	11.4	11.6	212	26.7	24.0	50.7	338	422	271	303	442	159
39	30.5	2000	84	30.09	607	8090	.0750	---------	206	12.2	12.1	12.1	212	26.7	24.1	50.8	344	430	277	306	462	157
40	30.5	2000	84	30.06	520	8090	.0643	---------	203	10.5	12.8	11.7	209	26.8	23.9	50.7	334	410	270	298	445	158
41	30.1	2000	86	30.08	729	8050	.0906	---------	206	11.4	10.5	11.0	211	26.9	24.1	51.0	330	411	268	301	422	162
42	30.5	2000	87	30.05	568	8080	.0703	---------	205	12.2	12.6	12.4	211	26.7	24.0	50.7	341	429	278	315	473	164
43	30.5	2000	89	30.03	688	8080	.0852	---------	207	12.3	11.2	11.7	212	26.6	23.9	50.5	342	418	264	302	444	161
44	30.2	2000	89	29.78	575	8050	.0714	---------	208	12.0	11.7	11.9	214	26.7	24.0	50.7	343	429	278	310	455	162
45	30.0	2000	91	29.79	746	8030	.0929	---------	208	11.7	9.9	10.8	213	26.5	23.8	50.3	326	406	266	292	409	158
46	30.2	2000	89	29.79	546	8060	.0677	---------	207	11.5	12.2	11.9	213	26.6	23.8	50.4	337	416	275	306	452	160
47	30.1	2000	91	29.81	705	8020	.0879	---------	207	12.3	10.6	11.5	213	26.7	24.0	50.7	329	412	270	296	439	160
48	30.3	2000	90	29.79	621	8030	.0774	---------	205	11.9	11.5	11.7	211	26.6	23.8	50.4	339	418	278	308	443	161
49	30.1	2000	89	29.79	663	8050	.0824	---------	204	11.9	11.1	11.5	209	26.6	23.6	50.2	338	414	272	299	433	162
50	17.1	1005	75	30.25	118	1370	.0861	---------	206	8.3	8.4	8.3	210	12.7	11.7	24.4	268	301	236	246	152	165
51	20.0	1200	75	30.24	198	2390	.0828	---------	204	9.6	10.3	10.0	208	15.2	13.6	28.8	287	322	244	267	216	165
52	30.0	2000	75	30.26	588	8020	.0733	---------	207	11.4	11.6	11.5	213	26.4	23.9	50.3	344	430	272	315	435	165

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TABLE I.- RESULTS OF TESTS ON ALLISON V-3420-11 ENGINE - Continued

Test	Manifold pressure (in. Hg abs.)	Engine speed (rpm)	Carburetor-air temperature (°F)	Barometric pressure (in. Hg abs.)	Fuel flow (lb/hr)	Engine-air flow (lb/hr)	Fuel-air ratio	Coolant-system pressure (lb/sq in. gage)	Coolant temperature into engine (°F)	Engine coolant temperature rise (°F)			Average engine coolant temperature (°F)	Engine coolant flow (lb/sec)			Cylinder-wall temperature (°F): Embedded thermocouple		Cylinder-wall temperature (°F): Spark-plug-gasket thermocouple		Engine heat rejection (Btu/sec)	Oil temperature into engine (°F)
										Left half	Right half	Av.		Left half	Right half	Total	Av.	Max.	Av.	Max.		
53	24.0	1500	76	30.27	295	4250	0.0694	---------	205	11.9	11.9	11.9	211	19.4	17.5	36.9	306	374	261	288	330	161
54	26.1	1710	71	30.26	403	5500	.0733	---------	206	11.6	10.8	11.2	211	22.2	20.0	42.2	322	393	261	299	355	167
55	37.1	2595	79	30.15	1305	13280	.0983	---------	203	10.9	10.1	10.5	209	33.6	30.2	63.8	350	439	282	313	505	165
56	35.0	2400	80	30.19	1001	11490	.0872	---------	205	11.0	10.5	10.7	210	32.6	29.1	61.7	350	443	281	323	496	165
57	33.0	2250	82	30.11	845	10100	.0836	---------	203	11.3	10.3	10.8	209	30.6	27.5	58.1	347	431	279	331	471	165
58	32.1	2150	84	30.09	735	9340	.0787	---------	204	11.8	11.1	11.4	210	28.7	26.1	54.8	347	432	278	310	469	165
59	28.2	1850	87	30.06	476	6680	.0712	---------	204	12.1	11.3	11.7	210	24.6	22.2	46.8	336	420	278	330	411	165
60	18.0	1105	80	30.09	157	1810	.0867	---------	205	9.1	9.3	9.2	210	14.2	12.6	26.8	269	307	237	255	185	165
61	21.0	1300	80	30.10	221	2860	.0773	---------	205	10.6	11.0	10.8	211	16.7	14.9	31.6	290	332	249	271	257	167
62	17.0	1005	80	30.10	126	1400	.0900	---------	205	7.7	8.4	8.1	209	13.7	11.2	24.9	259	294	230	247	151	165
63	20.0	1200	80	30.06	189	2220	.0851	---------	206	9.1	9.3	9.2	211	15.7	13.6	29.3	274	321	234	257	202	160
64	30.1	2200	87	30.07	704	8760	.0804	---------	204	10.6	10.3	10.4	210	29.6	27.0	56.6	333	415	276	319	442	161
65	30.0	2200	86	30.07	810	8740	.0927	---------	203	10.3	9.3	9.8	208	29.6	27.1	56.7	323	404	267	302	417	162
66	30.2	2200	89	30.06	614	8710	.0705	---------	203	11.0	11.1	11.0	209	29.6	26.9	56.5	341	424	279	336	466	163
67	30.3	2200	88	30.04	568	8670	.0655	---------	205	10.3	12.0	11.1	210	29.6	26.9	56.5	335	411	276	312	471	162
68	30.2	2200	88	30.04	584	8700	.0671	---------	204	10.6	11.5	11.0	209	29.4	26.8	56.2	336	415	272	292	464	181
69	30.0	2205	89	30.04	587	8690	.0676	---------	204	10.2	9.4	9.8	209	29.6	26.9	56.5	322	407	263	283	416	179
70	30.0	2200	86	30.04	564	8700	.0648	---------	205	10.7	9.7	10.2	210	29.6	26.9	56.5	326	411	268	287	433	161
Coolant mixture, 100 percent by volume ethylene glycol (AN-E-2).																						
71	37.0	2600	84	29.75	1258	13110	0.0960	---------	204	12.0	10.9	11.5	210	32.6	28.5	61.1	361	463	300	366	467	166
72	35.0	2400	84	29.75	1060	11540	.0919	---------	204	12.4	11.2	11.8	210	31.4	27.4	58.8	361	461	295	366	461	165
73	26.1	1700	89	29.74	384	5430	.0707	---------	204	13.2	12.7	13.0	211	22.6	19.9	42.5	333	422	285	334	367	164
74	23.0	1495	91	29.74	261	3780	.0690	---------	205	12.1	12.0	12.0	211	19.5	16.6	36.1	319	388	273	311	288	171
75	28.1	1850	84	29.74	475	6690	.0710	---------	205	12.3	12.4	12.4	211	24.5	21.7	46.2	338	432	287	340	381	165
76	32.1	2150	82	29.72	691	9280	.0745	---------	205	12.7	12.3	12.5	212	28.7	25.4	54.1	359	459	298	366	449	164
77	30.1	2000	82	29.73	552	7970	.0692	---------	205	12.1	13.3	12.7	211	26.7	23.6	50.3	356	448	297	357	425	163
78	30.1	2000	84	29.73	553	7970	.0694	---------	223	11.8	12.4	12.1	229	26.9	23.9	50.8	370	465	306	367	416	164
79	30.1	2000	82	29.73	552	7970	.0692	---------	186	13.6	14.0	13.8	193	26.4	23.4	49.8	347	445	282	347	448	165
80	30.0	2600	74	29.88	804	10010	.0803	---------	204	12.7	12.3	12.5	210	31.3	27.3	58.6	359	456	294	365	486	159
81	20.0	1300	84	29.89	214	2620	.0817	---------	206	10.2	11.5	10.9	211	16.9	13.6	30.5	296	341	252	278	221	172
82	17.0	1000	84	29.86	129	1460	.0884	---------	206	----	----	-----	210	12.5	10.6	23.1	263	302	236	256	---------	165
83	17.0	1100	90	29.98	135	1610	.0839	---------	205	----	----	-----	210	13.8	10.7	24.5	277	313	243	262	---------	168
84	18.0	1200	90	29.97	156	1630	.0957	---------	204	----	----	-----	209	15.3	13.3	28.6	282	325	251	271	---------	172
85	38.0	2600	83	30.20	1342	13430	.0999	---------	204	11.1	10.6	10.9	208	35.0	30.4	65.4	360	449	289	354	472	158
86	33.1	2250	83	30.19	857	10070	.0851	---------	205	12.0	10.8	11.4	211	30.1	26.6	56.7	359	450	292	362	430	158
87	17.1	900	87	30.19	114	1120	.1018	---------	203	----	----	-----	207	11.9	9.7	21.6	253	292	227	239	---------	164
88	16.0	1200	88	30.20	139	1610	.0863	---------	204	8.9	9.3	9.1	208	15.9	14.2	30.1	275	315	240	259	182	166
89	28.5	2200	84	30.19	556	7940	.0700	---------	204	11.1	11.8	11.4	210	29.4	26.3	55.7	351	441	279	362	422	159
90	20.1	2005	87	30.19	294	4210	.0698	---------	203	10.4	10.4	10.4	208	26.4	23.4	49.8	312	387	267	315	343	161
91	18.0	1700	87	30.19	205	2840	.0722	---------	205	9.9	9.9	9.9	210	22.1	19.4	41.5	297	355	254	287	273	164
92	17.0	1500	85	30.19	178	2310	.0771	---------	205	9.2	9.1	9.2	209	19.4	17.1	36.5	285	330	247	267	223	164
93	30.1	1495	83	30.02	467	6260	.0746	---------	205	14.5	13.8	14.1	212	19.3	16.9	36.2	345	427	286	336	340	166
94	28.7	1650	86	30.02	468	6260	.0748	---------	205	13.8	13.4	13.6	212	20.6	19.0	39.6	344	427	285	342	358	160
95	27.5	1800	85	30.02	469	6270	.0748	---------	205	12.9	12.4	12.7	212	23.7	21.1	44.8	337	428	283	341	379	163
96	22.0	2600	82	29.98	469	6260	.0749	---------	206	9.8	9.5	9.6	211	34.8	30.3	65.1	322	398	274	336	415	156
97	22.5	2500	83	29.98	468	6260	.0748	---------	205	10.1	9.9	10.0	210	34.1	30.2	64.3	321	397	272	330	427	153
98	23.0	2400	80	29.98	469	6280	.0747	---------	205	10.3	9.7	10.0	210	32.8	29.0	61.8	318	394	271	329	410	153
99	23.8	2250	79	29.87	470	6270	.0750	---------	204	10.4	10.4	10.4	209	30.0	26.8	56.8	325	400	282	339	392	158
100	24.9	2100	81	29.88	470	6270	.0750	---------	205	11.0	10.8	10.9	210	27.8	24.7	52.5	327	405	280	335	380	157
101	26.1	1950	83	29.86	470	6260	.0751	---------	205	11.9	11.4	11.7	211	25.7	22.9	48.6	331	416	278	335	378	164
102	18.0	2000	83	30.20	296	3680	.0805	---------	206	8.7	8.8	8.7	210	26.3	23.4	49.7	301	357	258	293	287	162
103	26.1	2000	86	30.20	523	6480	.0807	---------	204	11.1	10.4	10.8	209	26.4	23.5	49.9	333	416	280	332	358	166
104	34.2	2000	86	30.20	757	9440	.0802	---------	204	13.3	11.4	12.4	210	26.4	23.5	49.9	361	468	298	369	411	165

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TABLE I.- RESULTS OF TESTS ON ALLISON V-3420-11 ENGINE - Concluded

Test	Manifold pressure (in. Hg abs.)	Engine speed (rpm)	Carburetor-air temperature (°F)	Barometric pressure (in. Hg abs.)	Fuel flow (lb/hr)	Engine-air flow (lb/hr)	Fuel-air ratio	Coolant-system pressure (lb/sq in. gage)	Coolant temperature into engine (°F)	Engine coolant temperature rise (°F)			Average engine coolant temperature (°F)	Engine coolant flow (lb/sec)			Cylinder-wall temperature (°F)				Engine heat rejection (Btu/sec)	Oil temperature into engine (°F)
																	Embedded thermocouple		Spark-plug-gasket thermocouple			
										Left half	Right half	Av.		Left half	Right half	Total	Av.	Max.	Av.	Max.		
Coolant, water																						
105	22.1	1600	82	30.15	280	3830	0.0731	5	178	8.3	8.2	8.3	182	21.3	19.9	41.2	256	307	214	230	343	169
106	26.1	2000	86	30.18	475	6480	.0733	5	176	8.8	8.3	8.6	180	26.9	25.4	52.3	278	348	223	245	451	166
107	28.2	2205	91	30.18	576	7990	.0721	5	176	8.8	8.8	8.8	180	30.0	29.8	59.8	289	357	229	248	528	172
108	18.0	1200	93	30.18	161	1940	.0830	6	178	7.2	7.6	7.4	182	15.8	14.5	30.3	230	261	202	216	225	172
109	17.0	1000	93	30.17	123	1290	.0954	5	177	6.4	7.2	6.8	181	12.9	12.1	25.0	217	243	195	207	171	163
110	30.0	2400	91	30.14	712	9300	.0766	10	181	7.7	8.3	8.0	185	33.7	31.8	65.5	296	360	233	257	526	165
111	20.0	1400	91	30.13	214	2830	.0756	5	178	8.1	8.8	8.5	182	18.4	17.1	35.5	240	279	204	220	303	170
112	32.1	2600	86	30.18	1000	10880	.0919	14	194	7.2	7.3	7.2	198	37.0	34.1	71.1	300	365	240	262	514	161
113	34.1	2400	90	30.18	1037	11150	.0930	13	192	7.9	6.7	7.4	196	33.8	32.4	66.2	301	374	240	263	492	164
114	36.0	2500	83	30.18	1260	12440	.1013	---------	195	7.9	6.7	7.3	199	34.8	31.0	65.8	298	373	236	258	483	156
115	30.0	2000	85	30.18	692	8040	.0860	---------	195	8.7	7.5	8.1	199	27.2	25.8	53.0	295	362	237	259	431	163
116	30.1	2000	84	30.18	692	8040	.0860	---------	187	8.8	7.7	8.2	191	27.3	25.7	53.0	287	355	230	249	436	161
117	30.1	2000	87	30.18	691	8020	.0862	---------	176	8.3	7.9	8.1	180	27.2	25.5	52.7	279	347	220	244	428	164
118	24.2	1800	89	30.18	432	5090	.0849	13	178	8.1	7.5	7.8	182	24.1	22.4	46.5	254	319	211	233	364	165
119	24.1	1800	88	30.18	432	5080	.0850	13	186	8.2	7.1	7.6	190	24.1	22.5	46.6	267	322	217	237	356	160
120	24.1	1805	88	30.18	432	5080	.0850	13	195	8.1	7.2	7.6	199	24.1	22.6	46.7	271	328	225	242	357	161
121	24.2	1800	94	30.17	432	5070	.0852	13	202	7.7	7.3	7.5	206	24.3	22.9	47.2	275	337	230	248	356	160
Coolant mixture, 30 percent by volume ethylene glycol (AN-E-2)																						
122	20.0	1400	92	30.08	213	2800	.0761	13	177	9.1	8.8	8.9	181	18.2	16.7	34.9	245	288	210	230	287	161
123	20.0	1400	93	30.07	212	2800	.0757	13	195	8.5	8.7	8.6	199	18.2	16.6	34.8	263	304	224	244	278	165
124	20.0	1400	93	30.05	212	2800	.0757	13	213	8.2	8.2	8.2	217	18.0	16.7	34.7	278	318	240	260	266	166
125	32.1	2600	81	30.17	940	10910	.0861	13	196	8.1	7.9	8.0	200	36.0	33.6	69.6	309	383	247	274	517	165
126	34.1	2400	82	30.18	963	11140	.0865	13	195	9.3	8.6	8.9	199	33.1	30.7	63.8	316	394	248	278	527	155
127	36.0	2500	80	30.18	1118	12340	.0906	14	195	10.0	8.0	9.0	200	34.9	32.2	67.1	315	398	247	277	561	159
128	38.0	2600	77	30.18	1280	13500	.0948	14	196	9.3	8.2	8.7	200	36.7	33.9	70.6	316	398	244	270	572	160
129	28.1	2200	92	30.19	600	7880	.0762	13	196	9.3	8.3	8.8	200	29.9	27.8	57.7	304	372	242	267	472	161
130	24.0	1800	85	30.19	359	4980	.0721	13	195	9.1	8.2	8.6	200	24.0	22.2	46.2	---	----	----	----	369	165
131	24.1	1800	85	30.18	359	4980	.0721	13	212	8.8	7.9	8.4	216	24.0	22.3	46.3	---	----	----	----	364	165
132	24.2	1800	85	30.18	360	4960	.0726	13	177	9.1	9.1	9.1	182	24.0	22.3	46.3	---	----	----	----	389	165
133	26.1	2000	87	30.17	484	6380	.0759	13	195	9.3	8.9	9.1	200	26.6	25.9	52.5	---	----	----	----	444	165
134	30.0	2400	82	30.09	768	9480	.0810	13	179	8.4	8.3	8.4	182	33.1	30.5	63.6	---	----	----	----	493	165
135	30.1	2400	82	30.09	768	9460	.0812	13	213	8.3	8.4	8.3	217	33.5	31.0	64.5	---	----	----	----	501	165
136	30.1	2400	83	30.10	765	9460	.0808	13	196	8.6	8.5	8.6	200	33.0	30.7	63.7	---	----	----	----	509	165
137	30.0	2400	85	30.11	765	9440	.0810	8	195	8.5	8.5	8.5	199	33.6	30.5	64.1	---	----	----	----	506	165
138	30.1	2400	85	30.11	765	9440	.0810	0	194	8.9	8.7	8.8	199	32.3	29.6	61.9	---	----	----	----	506	165
139	18.0	1200	84	30.13	146	1950	.0749	13	196	7.4	8.4	7.9	200	15.4	14.1	29.5	---	----	----	----	217	162
140	22.0	1600	83	30.13	243	3780	.0643	13	195	----	----	-----	200	21.1	19.5	40.6	---	----	----	----	---------	167
141	17.0	1000	83	30.13	122	1310	.0931	13	195	6.2	6.6	6.4	199	12.6	11.7	24.3	---	----	----	----	145	158
Coolant mixture, 100 percent by volume ethylene glycol (AN-E-2)																						
142	30.0	2200	73	30.28	672	8390	0.0801		208	----	----	-----	213	29.7	26.5	56.2	---	----	----	----	---------	---------
143	30.2	2200	73	30.28	672	8390	.0801		247	11.0	10.1	10.6	252	27.6	25.0	52.6	---	----	----	----	384	---------
144	30.5	2200	75	30.28	672	8370	.0803		268	9.6	8.7	9.1	272	30.3	27.8	58.1	---	----	----	----	371	---------
145	30.0	2200	76	30.30	672	8350	.0805		185	12.6	10.9	11.8	191	29.4	26.0	55.4	---	----	----	----	426	---------
146	30.2	2200	77	30.30	672	8340	.0806		231	11.9	9.4	10.6	236	29.8	26.4	56.2	---	----	----	----	405	---------
147	28.0	1800	77	30.30	506	6310	.0802		231	11.3	9.5	10.4	236	23.9	21.5	45.4	---	----	----	----	320	---------
148	28.0	1800	75	30.29	506	6310	.0802		189	11.9	11.3	11.6	195	23.7	20.9	44.6	---	----	----	----	338	---------
149	28.3	1800	76	30.28	506	6310	.0802	5 to 15	268	10.5	8.9	9.7	272	23.9	21.7	45.6	---	----	----	----	311	---------
150	28.2	1800	77	30.28	505	6310	.0800		247	10.7	9.8	10.3	252	24.0	21.6	45.6	---	----	----	----	323	---------
151	28.0	1800	83	30.28	506	6270	.0807		177	13.5	11.4	12.4	183	23.5	20.8	44.3	---	----	----	----	356	---------
152	32.3	2400	75	30.16	835	10450	.0799		209	11.7	10.6	11.2	214	32.4	29.3	61.7	---	----	----	----	460	---------
153	32.2	2400	78	30.14	835	10400	.0803		191	13.3	10.6	12.0	197	32.5	29.2	61.7	---	----	----	----	484	---------
154	32.6	2400	79	30.13	835	10390	.0804		231	11.8	9.5	10.7	236	32.7	29.8	62.5	---	----	----	----	454	---------
155	32.7	2400	81	30.14	835	10370	.0805		249	10.6	9.6	10.1	254	32.5	29.8	62.3	---	----	----	----	435	---------
156	32.6	2400	83	30.13	835	10350	.0807		268	10.7	9.3	10.0	273	31.1	28.7	59.8	---	----	----	----	420	---------

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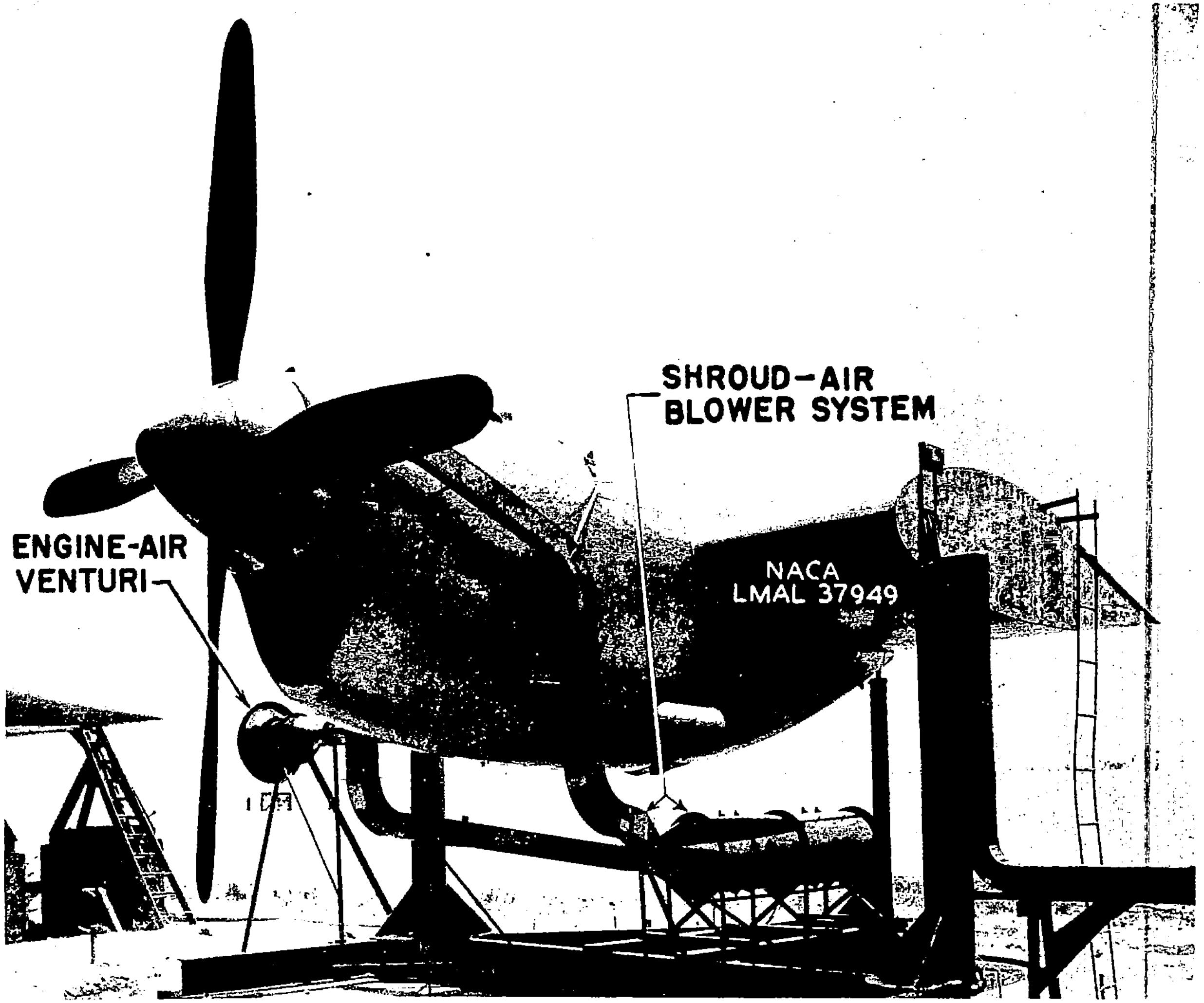

Figure 1.- Engine-nacelle test setup for cooling tests of the Allison V-3420-11 engine.

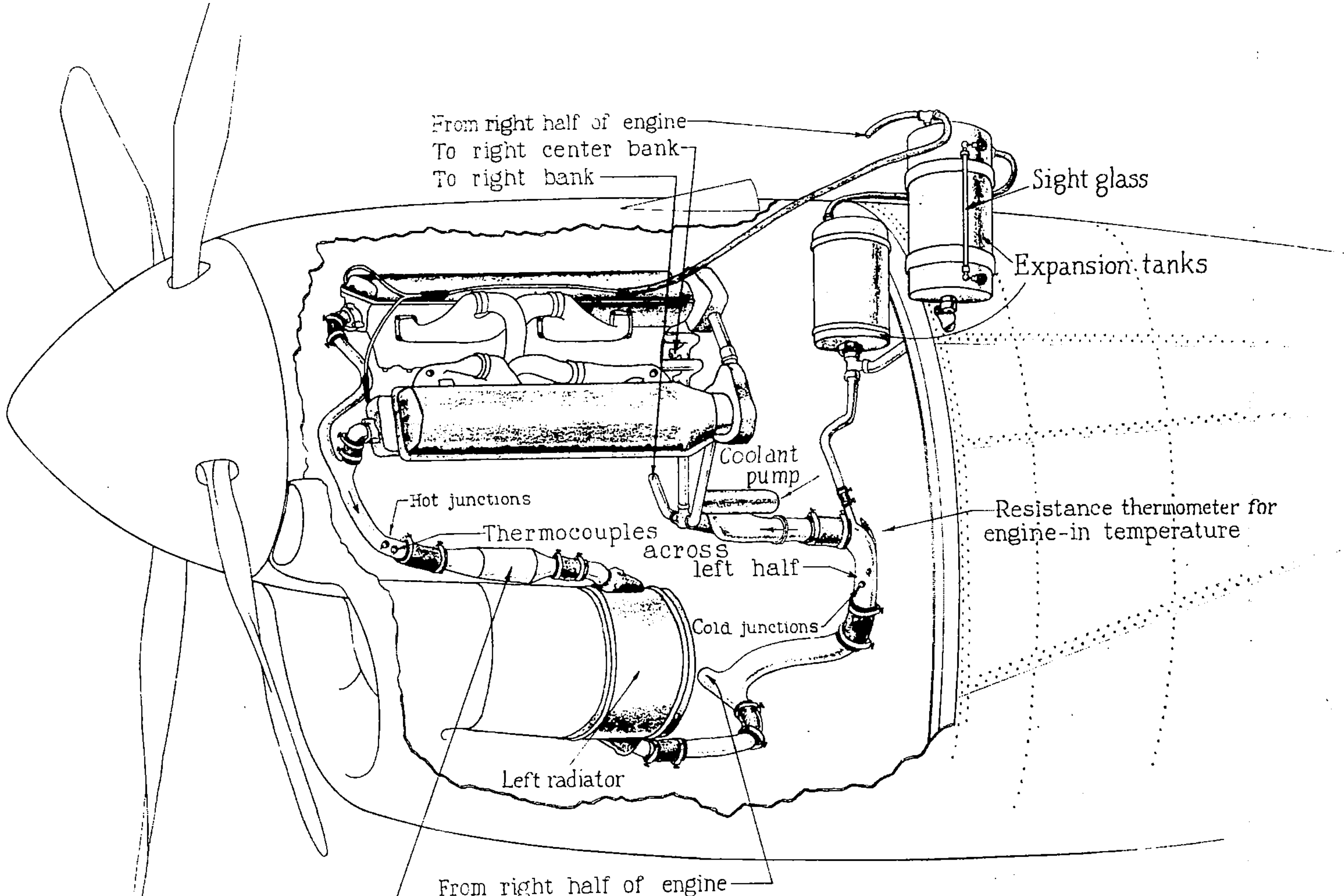

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Figure 2.-Location of coolant flowmeter and thermocouples for left half of engine.

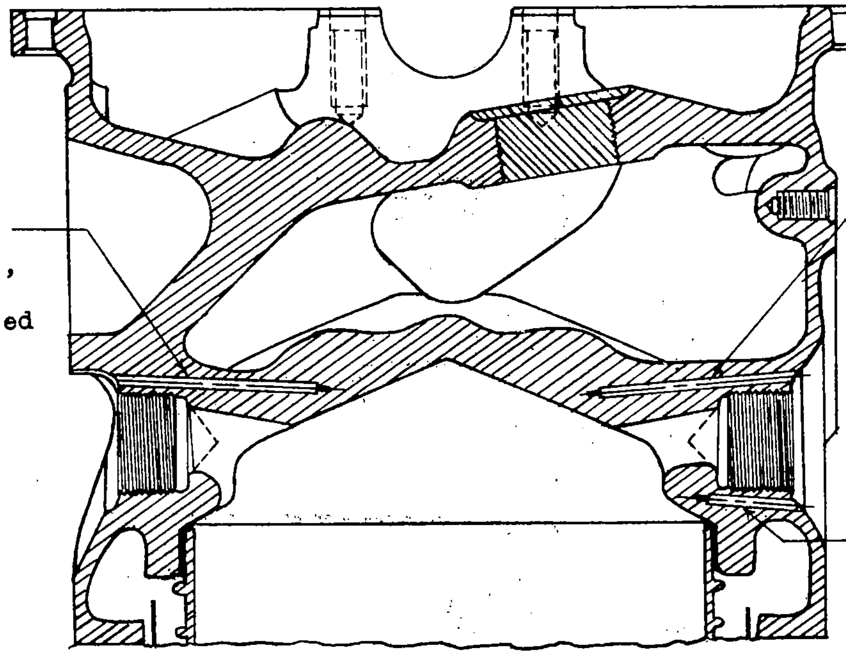

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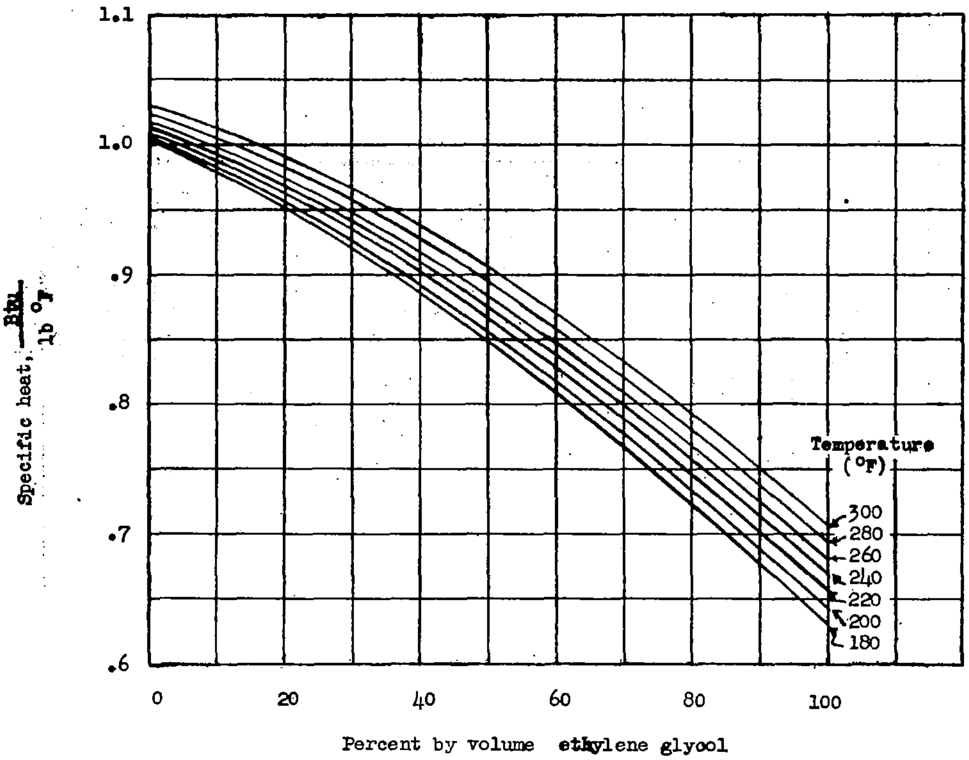
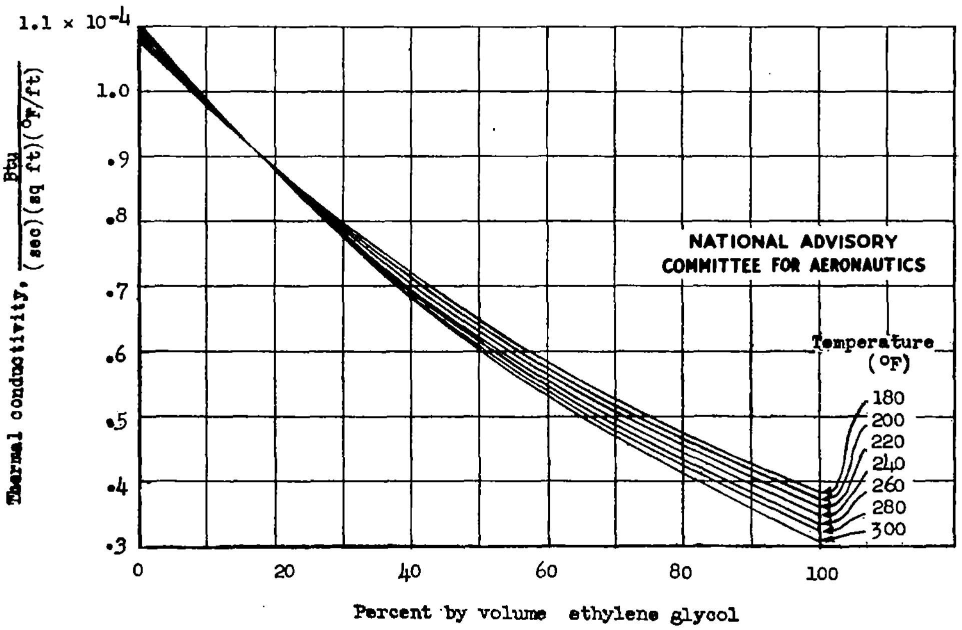
Figure 3.- Location of embedded thermocouples in cylinder wall.

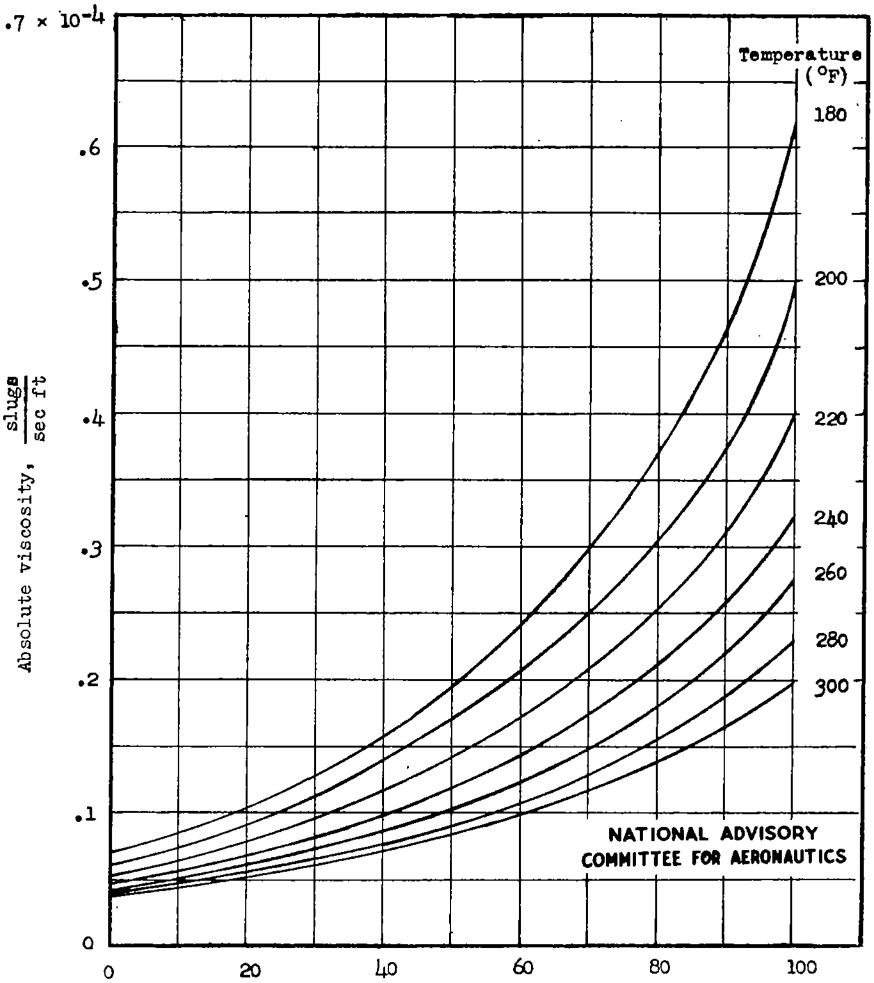


(a) Specific heat.



(b) Thermal conductivity.

Figure 4.- Physical properties of mixtures of pure ethylene glycol and water. (From reference 4.)



Percent by volume ethylene glycol

(c) Absolute viscosity.

Figure 4.- Concluded.

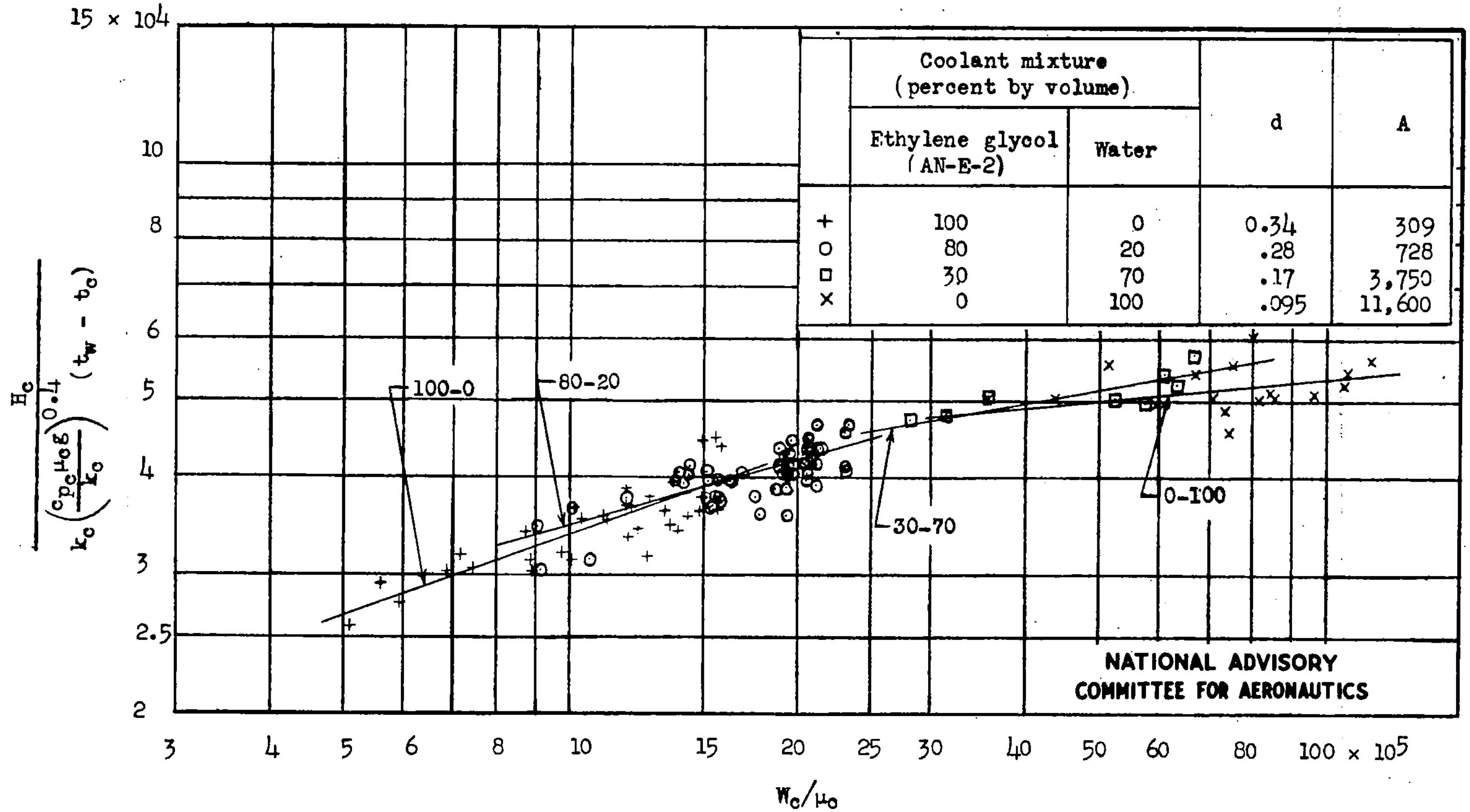


Figure 5.- The effect of W_c/μ_c on the rate of heat transfer from the cylinder walls to the coolant.

MR No. L5D03

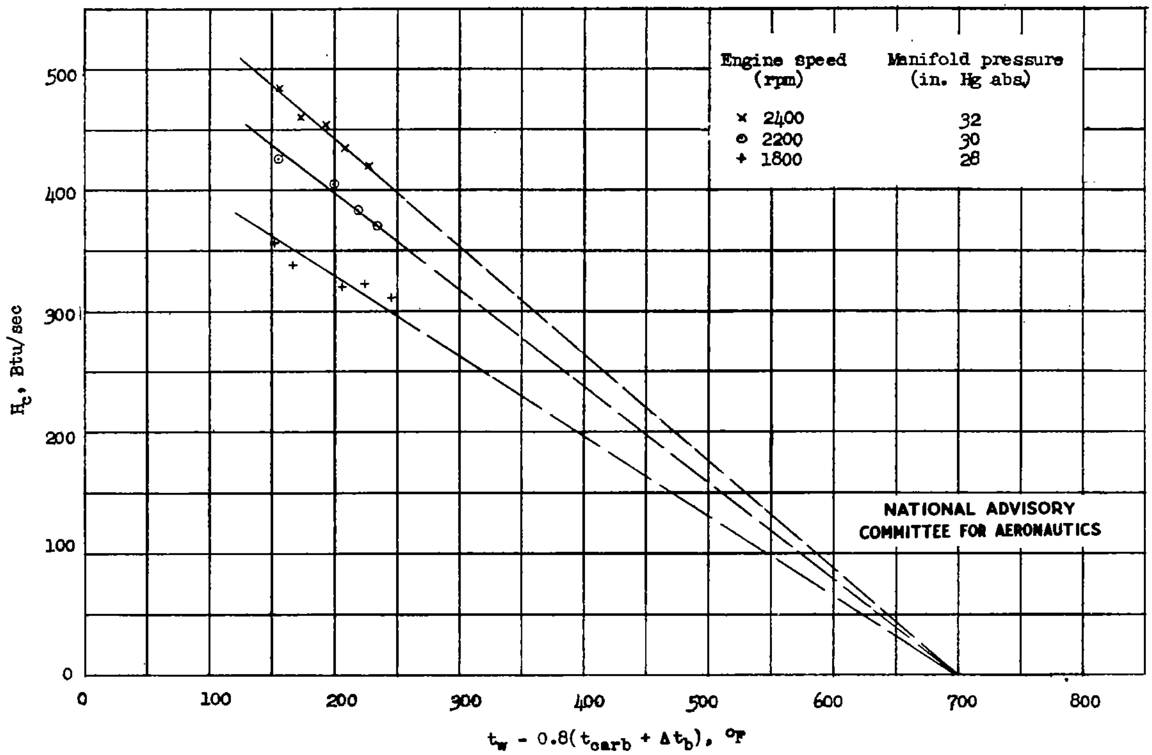


Figure 6.- The variation of the heat transfer from the cylinder walls to the coolant with the average cylinder-wall temperature; fuel-air ratio, 0.08.

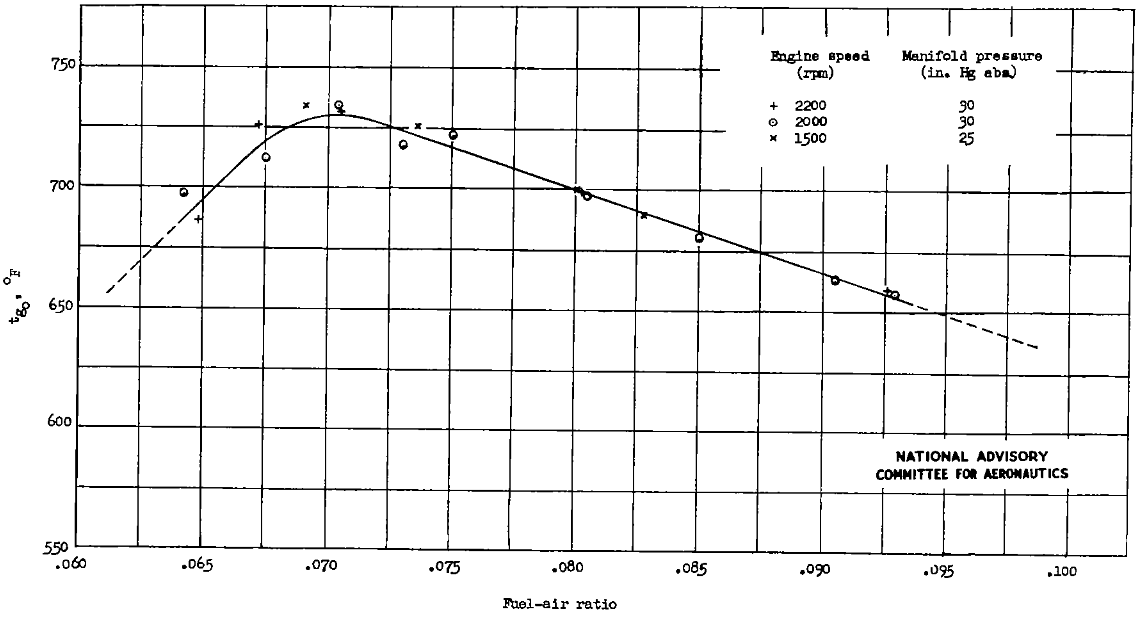


Figure 7.- The variation of t_{g_0} with fuel-air ratio.

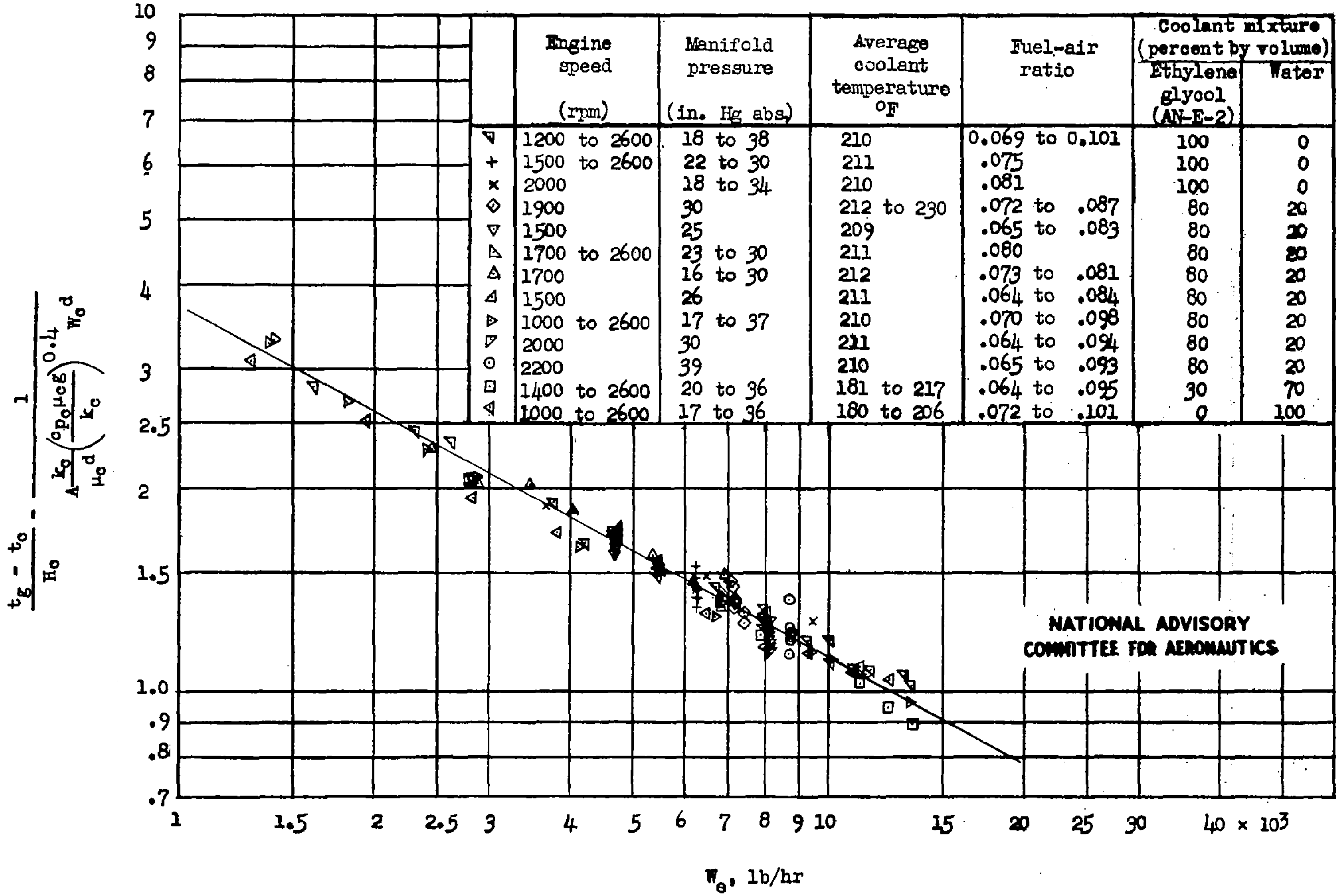
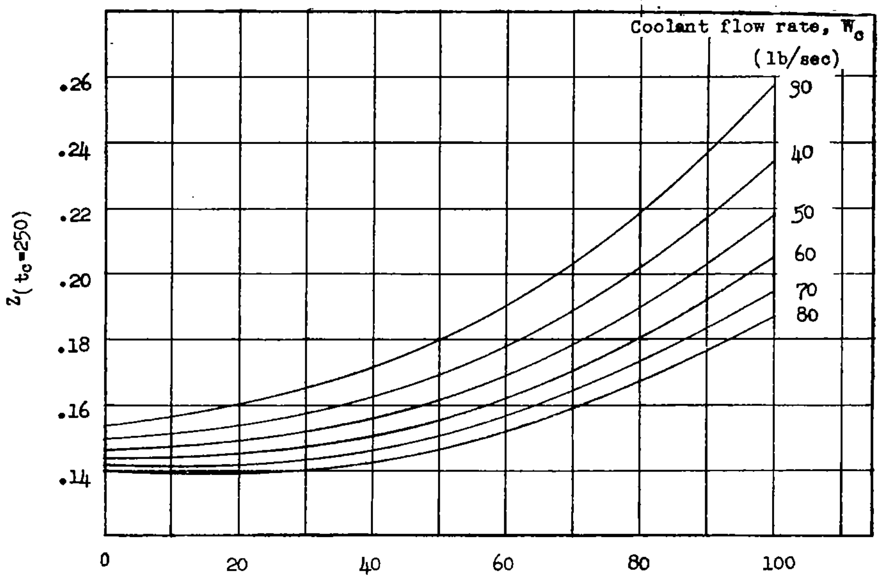
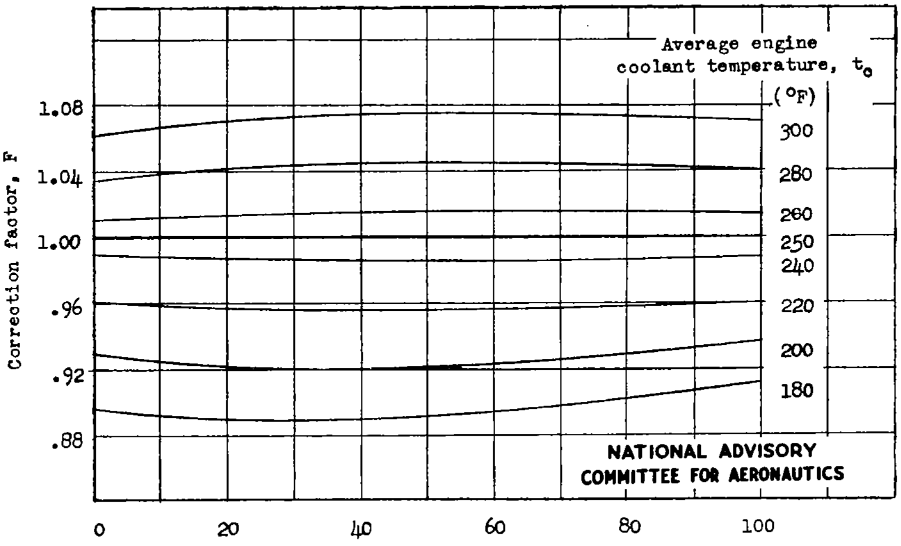


Figure 8.- Heat-rejection characteristics of the Allison V-3420-11 engine.

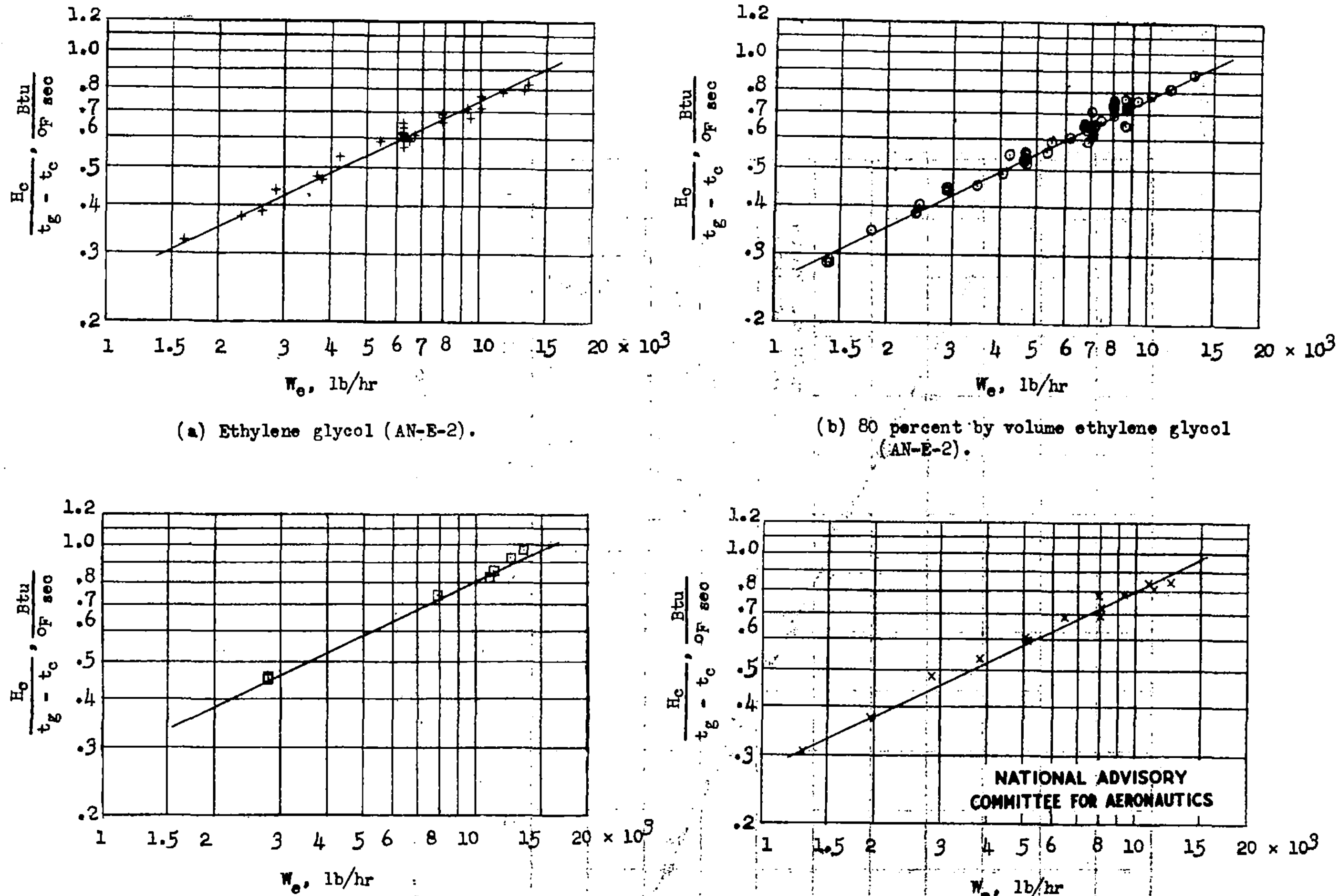


(a) Values of Z for an average engine coolant temperature of 250° F.



(b) Correction factor to be applied to $Z_{(t_c=250)}$ to obtain Z for average engine coolant temperatures other than 250° F.

Figure 9.- Curves for determining Z or $\dfrac{1}{A\dfrac{k_c}{\mu_c d}\left(\dfrac{c_{p_c}\mu_c g}{k_c}\right)^{0.4} W_c{}^d}$ for various coolant mixtures, average engine coolant temperatures, and coolant flow rates. $Z = FZ_{(t_c=250)}$.



(a) Ethylene glycol (AN-E-2).

(b) 80 percent by volume ethylene glycol (AN-E-2).

(c) 30 percent by volume ethylene glycol (AN-E-2).

(d) Water.

Figure 10.- The effect of engine-air flow on the heat rejection to the coolant for each of the coolant mixtures used in the tests. Effect of variation in coolant temperature on coolant properties neglected.

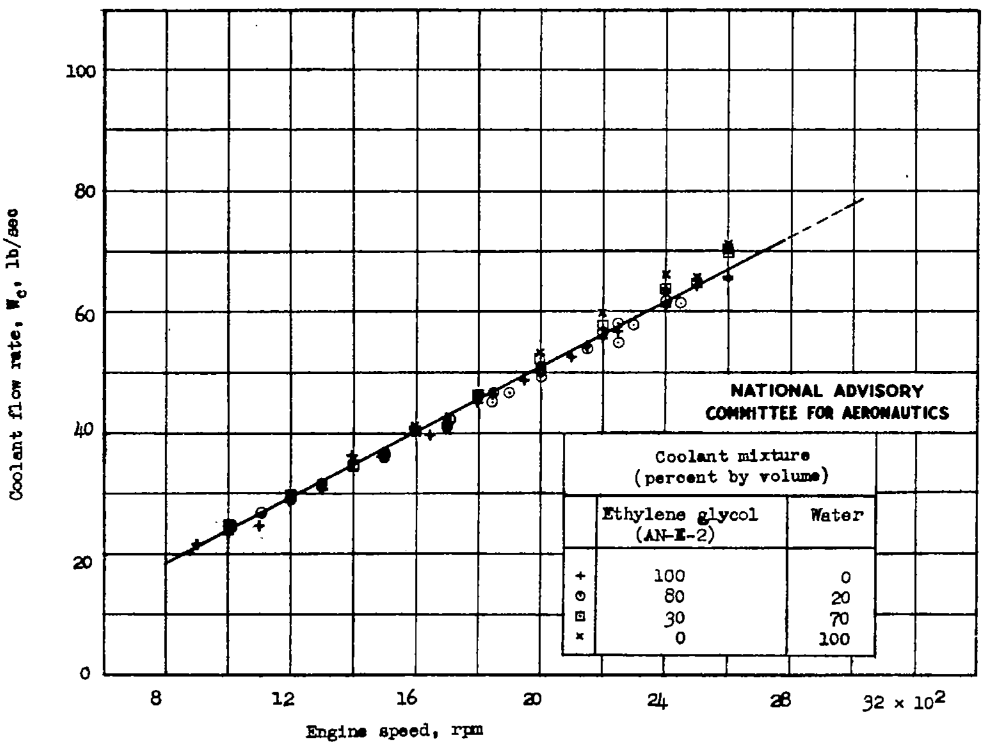


Figure 11.- The effect of engine speed on the coolant flow rate for various coolant mixtures.

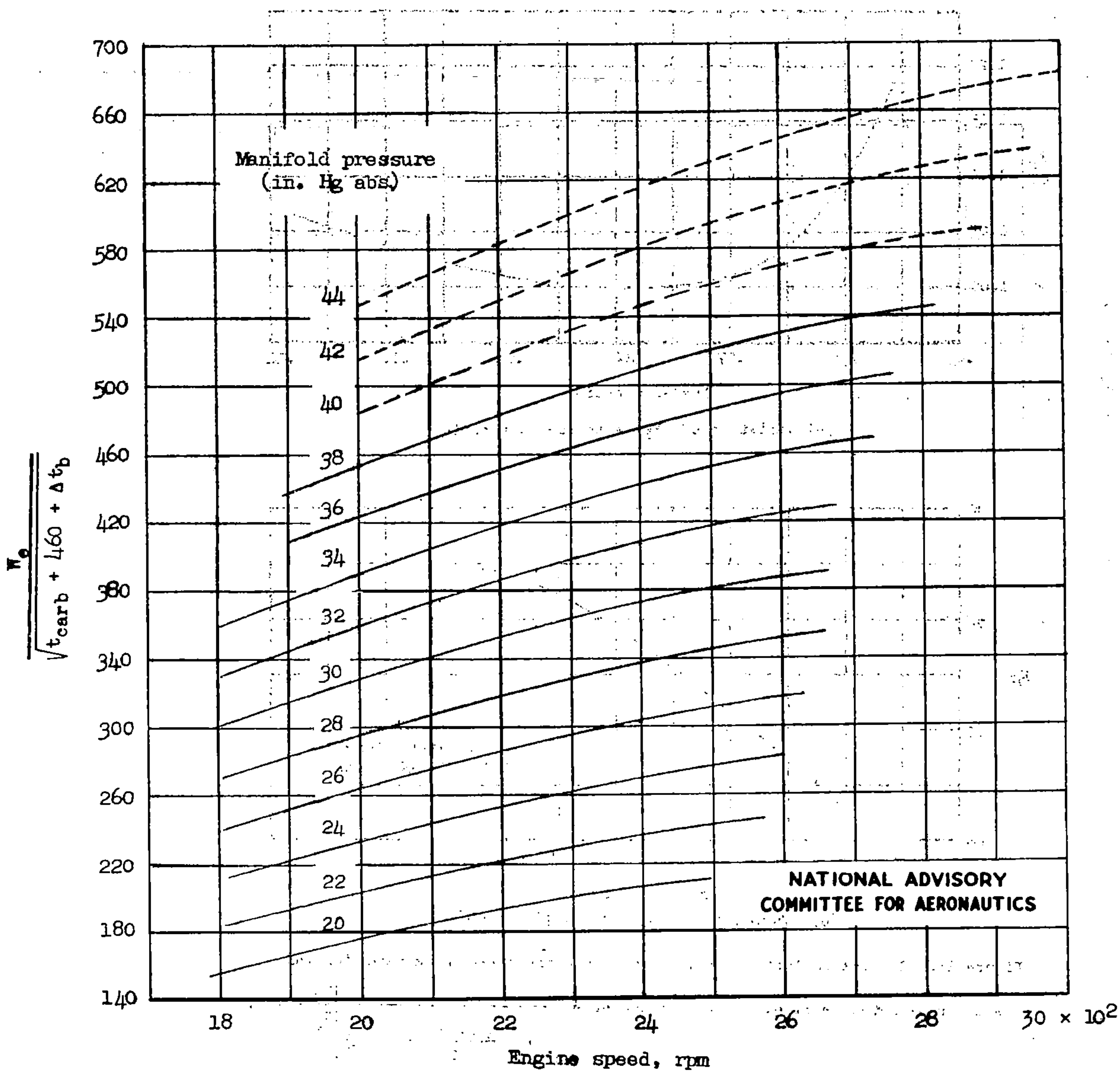
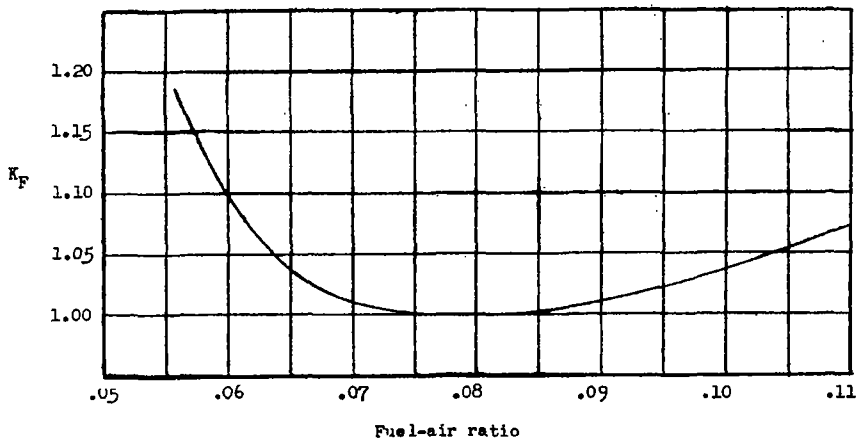
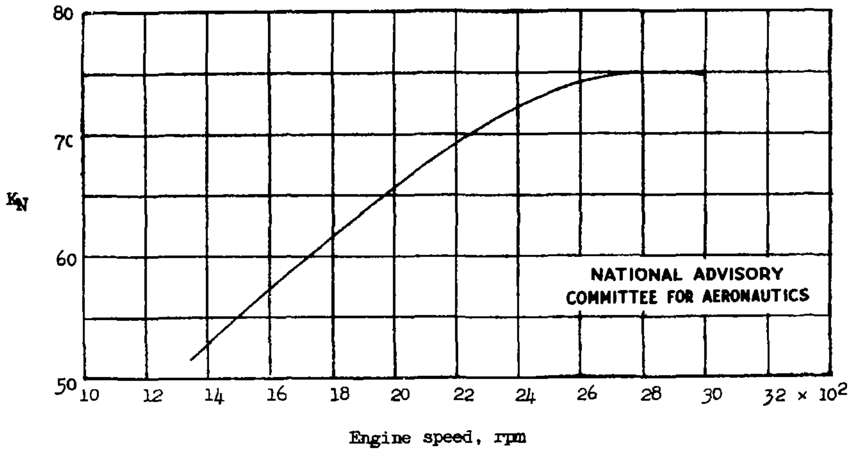


Figure 12.- Variation of engine-air flow with engine operating conditions. Exhaust back pressure, 30 inches of mercury absolute.



(a) Variation of K_F with fuel-air ratio.



(b) Variation of K_N with engine speed.

Figure 13.- Correction factors used to calculate the brake horsepower for the Allison V-3420-11 engine. Brake horsepower = $\left[\dfrac{p_m}{1 + \dfrac{t_{carb} - 80}{10}(0.01)}\right]\dfrac{K_N}{K_F} - 700.$